(A) TITLE OF THE INVENTION

ILLUMINATION COMPENSATOR FOR CURVED SURFACE LITHOGRAPHY

(B) CROSS-REFERENCE TO RELATED APPLICATIONS

(Not Applicable)

(C) STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

(Not Applicable)

(D) REFERENCE TO A MICROFICHE APPENDIX

(Not Applicable)

E) BACKGROUND OF THE INVENTION

(1) <u>**Field Of The Invention**</u>

This invention relates to projection lithography systems for imaging onto curved substrates, and more particularly relates to a large-area lithography system featuring a curved mask that is identical in size and shape to the curved substrate. An axially moving 1:1 projection lens achieves a constant optical path length for conjugate image points in order to maintain the substrate surface within the depth-of-focus, thereby providing an effective depth-of-focus much larger than the depth-of-focus of the projection optics itself. This invention is centered around a novel illumination compensator which we call 'Zerogon', that is part of an illumination system and protects the converging illumination beam

from various image anomalies when it transmits through a curved mask. This unique optical system with curvatures on its elements has zero power and works like an un-tilted plane glass blank in the path of a given collimated or convergent beam. A detailed paraxial ray theory was developed to demonstrate the functionality of such a device. Two possible configurations for Zerogon have been described in the invention. The unique device facilitates patterning on curved surfaces by means of small-field seamless scanning techniques to achieve high resolution over an entire large-area curved substrate. The concept of compensation described here is applicable in any generic optical system involved with illumination or imaging beams.

(2) **Description Of Related Art**

Introduction to optical projection lithography

In the recent past, electronics industry has witnessed dramatic increase in performance, throughput, yield and cost reduction with the advances in optical projection lithography. On the other hand, detector technology promises tremendous future for curved focal plane arrays (FPAs) in strategic and astronomical applications. Contact and non-contact projection lithography faces several challenges in patterning intricate details on curved surfaces. Anvik's systems are designed based on a novel, hexagonal seamless scanning concept and single-planar stage system configuration that provide both high optical and scanning efficiencies, and combine high-resolution imaging with very large exposure area capability. The prior art of Anvik's techniques for imaging on curved substrates has a curved mask that is identical in size and shape to the curved substrate for 1:1 patterning. There is a good description of curved-mask

lithography in US Patent 6,416,908, PROJECTION LITHOGRAPHY ON CURVED SUBSTRATES, Klosner, Zemel, Jain & Farmiga, July 9, 2002. However, a curved mask, because of its finite thickness, can cause several image anomalies due to its interaction with the illumination beam. In this invention, we propose and use a novel optical device, which we call 'Zerogon' that compensates for the image degradation associated with the use of curved masks.

Importance of the illumination system

It has been a well-known fact from the times of invention of the microscope that the resolution and contrast of the microscope are significantly influenced by the technique of illumination of the sample. Similarly, the illumination technique can make a significant impact on the resolution and contrast of a lithographic projection system too. Though the illumination system is probably the most neglected or ignored part in such systems, some recent advances in illumination systems play great role in controlling the performance such as resolution, depth of focus and image contrast of a lithographic projection system. A few of these techniques are popularly known as off-axis illumination, annular source illumination, slit source illumination, 2-point source illumination, SHRINC illumination and use of phase shift masks.

Brief review of existing illumination techniques for planar masks

It has been an established fact that the use of curved Focal Plane Arrays (FPAs) can significantly influence the space and military applications in achieving wide fields-of-view for their sensors. Some of the techniques used for manufacturing these curved FPAs use curved masks in their projection systems. The several illumination techniques described above assume the use of planar masks in the object plane of the projection system. Use of curved masks in the object plane can cause severe image degradation due to defocus and beam deviations at the curved object plane. Problems associated with defocus of the condensed beam at the curved mask surface can be addressed by using special image motion compensating techniques within the condenser and the projection lens. On the other hand, beam deviations at the curved mask surface can significantly impact the light coupling between condenser and the projection lens affecting the partial coherence factor, which is the ratio of numerical apertures of condenser and the projection lens. A partial coherence factor value of 0.7 is normally chosen for incoherent illumination to achieve best resolution with projection lithography. In this paper, we describe a novel method to control the beam deviations at the curved mask plane, thereby protecting the partial coherence factor and the resolution characteristics of the imaging system.

(F) BRIEF SUMMARY OF THE INVENTION

This invention provides to a large-area lithography system the capability of patterning onto a curved substrate, using a curved mask in order to achieve a fixed track length for conjugate object and image points, by linearly moving a 1:1 projection lens for compensation on a small-field seamless scanning platform, thereby maintaining the curved substrate surface within its depth-of-focus, and by providing an effective coupling of the illumination beam from the curved mask to the projection lens, thereby preserving the partial coherence factor and the related resolution characteristics

This invention provides these capabilities while retaining the option of small-field seamless scanning techniques to achieve high resolution over the entire large-area curved substrate.

The object of the invention is to make possible a high-resolution projection imaging operation on a curved substrate with topographical variations significantly greater than the depth-of-focus of the imaging optics.

Another object of the invention is to permit scanning projection imaging, by providing an effective solution for beam coupling mechanism using an innovative optical system called 'Zerogon' that carries the curved mask on one of its surfaces.

Another innovative feature of the invention is to provide a unique design for Zerogon by means of a symmetric arrangement of two identical meniscus optical elements so that it works as a null compensator for collimated or converging beams interacting with a curved mask and thus causing negligible deviation or shift of the beam passing through such a device.

An advantage of such unique configuration for Zerogon is that the design could be scaled up to conduct large-area curved patterning with relatively smaller cross-section of scanning convergent beam imaging on one of its outer surfaces thus facilitating large-area seamless scanning for curved –curved lithography.

Other objects, features and advantages of the invention will be apparent to those skilled in the art, in view of the drawings and written description.

(G) BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

Figure 1 is a simplified semidiagrammatic elevation view of a preferred embodiment of the invention, showing a compensated curved mask with Zerogon and curved substrate that lead to an effective beam coupling,

Figure 2 is a simplified semidiagrammatic elevation view of a PRIOR ART imaging system similar to the preferred embodiment of the invention, showing uncompensated curved mask and curved substrate that lead to an ineffective beam coupling in a folded mask-on-stage projection embodiment of PRIOR ART.

Figure 3 illustrates the basic illumination characteristics in projection lithography, in which the PRIOR ART mask, usually in the form of a grating, diffracts the incoming beam into zero-and-higher orders.

Figure 4 is a PRIOR ART showing illumination characteristics in projection lithography under coherent illumination.

Figure 5 is a PRIOR ART showing illumination characteristics in projection lithography under incoherent illumination.

Figure 6 is a diagram showing how a meniscus lens shifts the light beams passing through it, and if allowed to carry the mask on its outer surface, can cause an ineffective coupling of the illumination beam to the projection lens.

Figure 7 is a PRIOR ART diagram showing how the conventional lens pair called the "Hypergon" acts as an imaging system and is significantly different from Zerogon in construction and performance.

Figure 8 is a diagram showing how a lens pair, such as the Zerogon, transmits the light beams without any deviations, and hence can provide an effective coupling of the illumination beam to the projection lens.

Figure 9 is an unfolded diagram showing how the Zerogon-mask combination helps the projection lens collect the necessary diffraction orders.

(H) DETAILED DESCRIPTION OF THE INVENTION

Figure 1 and Figure 2 show the preferred embodiment for patterning onto curved substrates by using a Zerogon lens pair 1, mask 2 having a curvature that is identical to that of the substrate 3 (i.e., the size and shape of the mask 2 and substrate 3 are the same) by additionally performing the imaging using a 1:1 projection imaging system featuring reverser 4, projection lens 5, and fold mirrors 6 as required in directing the patterning beam from illumination source 7 to substrate 3. Stage 8 provides scanning motion. All elements of Figure 2 (PRIOR ART) are also present in Figure 1. The difference between the system of Figure 1 and the PRIOR ART system of Figure 2 is the presence of the Zerogon in Figure 1 and the absence of the Zerogon in Figure 2. The Zerogon

in Figure 1 provides an effective beam coupling between the curved mask and the projection lens.

We hereby discuss the basis of our invention, initially dealing with planar masks and then with the problems associated with thick curved masks. The discussions would finally evolve into the subject of the current invention that significantly improves the performance of curved mask lithography.

Patterning on curved surfaces using an Anvik seamless scanning system - - PRIOR ART – FIGURE 2

Figure 2 illustrates the configuration of a curved mask and curved substrate when lithography is performed utilizing an Anvik large-area seamless scanning microlithography system, as described in US Patent No. 6,416,908, issued July 9, 2002. The Anvik system uses a hexagonal image field to achieve seamless scanning, and a reverser unit, which maintains the required image orientation on the substrate. Elements of greatest significance in Figs. 1 & 2 are: curved mask 2; curved substrate 3; reverser 4; projection lens 5, illumination source 7 and scanning platform 8. The curved substrate 3 and curved mask 2 are situated on a common scanning platform 8, simplifying the overall system design. Note that since this is a seamless scanning system, the mask can be significantly larger than the image field. When the Anvik system is configured using this invention for patterning a curved mask onto a curved substrate, the mask and substrate sit on the single scanning platform, with the mask oriented in an inverted manner with respect to the substrate. With this configuration, a constant track length is maintained from any object point on the mask to its conjugate image point on the substrate. Separate means of oppositely directed

motion provide motion to projection means 5 to correct defocus due to curved object surface and curved image surface. The illumination means typically includes condensing means having zoom capability to keep the size and focus of the illumination beam constant on the mask.

Basic illumination characteristics

Illumination systems with planar masks

All the lithographic tools based on optical projection lithography employ an illumination system that transmits uniform illumination through a mask from a laser source to the projection lens. The mask, usually in the form of a grating, diffracts the incoming beam into zero- and higher orders depending on the period *d* of the mask, wavelength of operation λ and angle of incidence φ as given by the following relation,

$$d(\sin\theta - \sin\varphi) = n\lambda \tag{1}$$

where θ is the angle of diffraction of order n. The spatial information about the mask is contained in the diffracted light. To achieve the perfect edge definition in the image plane all spatial frequencies of the mask must be captured by the projection lens and combined with zero-order beam at the image plane. Aerial image quality begins to suffer when the projection lens can no longer transmit the higher-order frequencies. At the limit of resolution, only one or the both of the first-order beams are collected and combined with the zero-order beam. Beyond the resolution limit of the lens, the diffraction angle produced by the feature size is so large that the lens cannot transmit even the first-order beams and only the

zero-order beam is transmitted producing a uniform irradiance in the image plane. The modulation or contrast and thus the resolution of the image is then totally lost beyond the theoretical limit of resolution.

The resolution limit and contrast of the image are typically defined by the degree of coherence of the illumination beam. In the coherent case, light is collimated perpendicular to the mask, and the light diffracted through the mask with an angle θ is captured by the projection lens provided θ ≤ NA of the projection lens. In the case of incoherent illumination, light can be diffracted at 2NA and still be collected by the projection lens so that the first-order beams can combine with the zero-order beam to provide the limited resolution. Thus, from equation (1) the highest spatial frequency ν_{max} that can be imaged by the projection lens under coherent and incoherent illumination can be written as

$$\begin{aligned} \nu_{\max\_coherent} &= \frac{1}{d} = \frac{NA}{\lambda} \\ \nu_{\max\_incoherent} &= \frac{1}{d} = \frac{2NA}{\lambda} \end{aligned} \tag{2}$$

Though incoherent illumination provides twice the resolution as that of coherent illumination, higher spatial frequencies suffer from lower contrast in the projected image under incoherent illumination. It has been an established practice since the age of microscope to choose an optimum partial degree of coherence σ between the two extremes to balance the resolution and contrast. σ is often referred to as partial coherence factor and is defined by the ratio of NA of illumination system to that of projection system.

$$\sigma = \frac{NA_{illu\min ation}}{NA_{projection}} \qquad (3)$$

For cases of NA of illumination system tending to zero or a collimated beam, σ=0(coherent); and for cases where NA of illumination system equals or becomes greater than that of projection system, $\sigma \geq 1$(incoherent). It is generally considered that the best illumination for optimum pattern transfer in conventional photoresists is by setting a σ value of ~0.7 (partial coherence).

Problems associated with uncompensated curved masks

It is now easy to realize the importance of an effective coupling between illumination system and the projection lens by means of partial coherence factor in the field of projection imaging. Use of planar masks at the intermediate focus obviously does not pose any challenge to any projection mechanism as they neither deviate nor distort the illuminated beam. On the other hand, a curved mask surface can significantly distort the transmitting illuminating beam, depending on the structure of the mask device, causing sever image anomalies and loss of resolution. In this invention, we enhance our prior art Anvik system for curved surface lithography with a new illumination compensator that eliminates practically all the problems associated with a curved mask.

Design of a curved mask compensator

Design principles of such a device

The basic goal of designing an illumination compensator for a curved mask is to transmit the converging scanning beam undistorted in its direction and

position of exit while it excurses over the curved mask during scanning. The direction of the chief ray of the converging beam is preserved to maintain an effective coupling so that the lens collects the necessary diffracting orders. Angle of each ray with respect to chief ray within the converging beam is preserved to maintain the numerical aperture of the illumination system, and thus the partial coherence factor. This essentially calls for such an optical device, which holds the curved mask and acts like an optically powerless component as in the case of a planar mask. The basis of this invention is centered on such an optical device that is transparent to the incoming radiation and holds the curved mask on one of its outer curved surfaces and transmits the radiation without any significant image anomalies.

In this section we derive some basic relationships among the constructional parameters of such a device. Let us think of a positive meniscus element with its convex surface as the mask carrier for the purpose. Initially, we derive some basic relations in the context of using such a single meniscus element. In the later part, we discuss some major advantages of using a symmetric meniscus doublet for holding a curved mask on one of its outer surfaces.

We derive here the basic paraxial relationships among the constructional parameters to design and understand the behavior of meniscus elements in the context of using them as illumination compensator. The equations are based on the standard paraxial trace of a given ray within the optical system. The symbols

in these equations have the following meaning with subscripts indicating the surface number under discussion.

u and u' are the slopes of the ray before and after refraction at a given surface;

y is the height of the ray on a surface;

t is the vertex spacing between two consecutive surfaces;

n and n' are refractive indices of the medium before and after refraction

<u>Meniscus element:</u>

Let the radii of curvature of the surfaces on a meniscus element be R_1 and R_2. For a ray traveling at angle u_1 and striking the first surface at height y_1, the refraction is given by

$$u_1' = \frac{nu_1}{n'} - \frac{y_1(n'-n)}{R_1 n'}$$

For first element, n' = N and n = 1, where N is the refractive index of the glass material of the element. Thus,

$$u_1' = \frac{u_1}{N} - \frac{(N-1)}{N}\frac{y_1}{R_1} \tag{4}$$

The ray transfers and intersects the second surface at

$$y_2 = y_1 + t_1 u_1' = \left(1 - \left(\frac{N-1}{N}\right)\frac{t_1}{R_1}\right)y_1 + \frac{t_1}{N}u_1 \tag{5}$$

Refraction at second surface may now similarly be derived as eqn.(4) and on simplification we get,

$$u_2' = u_1 - (N-1)\left[\frac{y_1}{R_1} - \frac{y_2}{R_2}\right] \tag{6}$$

At this moment it is worth making a note on the performance of a single meniscus element with ray entering on concave surface and emitting from the convex surface as shown in Figure 6. In order to perform like non-deviating element for a given ray with slope u_1, we would like to have

$$u_2' = u_1$$

and, Eqn.(6) would then give

$$\frac{y_1}{R_1} = \frac{y_2}{R_2} \qquad (7)$$

On substitution of Eqn.(5) in Eqn.(7), we get

$$R_1 - R_2 = \frac{(N-1)}{N} t_1 - \frac{t_1 u_1 R_1}{N y_1} \qquad (8)$$

As explained earlier, the objective of designing this optical system is to transmit the collimated or converging beam undeviated without any lateral shift when the optical system moves perpendicular to its optical axis. In the case of a single meniscus Eqn. (8) is never satisfied, as the constructional parameter ΔR (i.e., R_1-R_2) is a function of both thickness and u_1. The dependence of ΔR on u_1 can only be eliminated for collimated beam for which u_1=0. However, for the ray in a convergent beam with $u_1 \neq 0$, Eqn. (7) is never satisfied and $u_2' \neq u_1$, affecting partial coherence factor when the convergent beam excurses over a curved surface. The dependence of ΔR on t_1 is possible for a meniscus with identical radii of curvature with zero thickness. It is, however, hard to realize such a meniscus optical element with negligible thickness capable of transmitting UV radiation.

On the other hand, a meniscus optical element with finite thickness can be made to have selected radii of curvature in compliance with Eqn. (8) so that

the element would not deviate an axial or collimated ray (with $u_1 = 0$) after refraction through the element. That is,

$$\Delta R = R_1 - R_2 = \frac{(N-1)}{N} t_1 \tag{9}$$

However, for a beam with ΔR given by Eqn. (9), Eqn. (5) gives us,

$$\Delta y = y_1 - y_2 = \frac{(N-1)}{N} \frac{t_1 y_1}{R_1} = \frac{\Delta R y_1}{R_1} \tag{10}$$

Even for collimated beams with $u_1 = 0$, Eqn. (10) still predicts the unwanted lateral shift Δy. In summary, Eqns.(6) – (10) describe that a single meniscus element with finite thickness needs to have different radius of curvature on each of its surfaces as given by Eqn. (9) to make the ray of a collimated beam undeviated after passing through the element. However, for the ray in a convergent beam with $u_1 \neq 0$, Eqn. (7) is never satisfied and affects the numerical aperture and also the partial coherence factor especially when the convergent beam excurses over a curved surface. Also, the ray undergoes a lateral shift Δy as given by Eqn. (10) that is a function of ray height y_1 on front surface. Thus a single meniscus element suffers from both drawbacks of deviating and shifting the ray laterally on second surface depending on the ray angle and its height on first surface. This is very undesirable for scanning systems such as seamless scanning technique because the beam or the ray excurses nonuniformly over the second surface. This would call for a complicated scanning mechanism to make the beam travel uniformly on the curved surface. Hence, a single meniscus element would not serve the required

purpose of an illumination compensator for curved masks in making the beam transmit without deviation or shift.

Zerogon:

The Goerz Hypergon lens (U.S.Patent 706,650-1902), a traditional photographic objective, consists of two symmetrical menisci equidistant on either side of the aperture stop. The inner and outer radii of curvature of the Goerz Hypergon differ by only one-half percent, producing a very flat Petzval curvature even at very large field of view. The aperture stop between the menisci is important in the Goerz Hypergon lens; this arrangement generates lens power as shown in Figure 7. However, in the current application we need to project the condensed beam onto a curved surface of an optical system, which on refraction would not deviate the beam. This calls for a zero-power optical system, the outer surface on which the converging illumination beam is in focus, scans the curved surface with the help of unitary stage. In other words, we need to consider an optical system with diameter larger than the scanning beam. The purpose of such an optical device is not to deviate the transmitted beam on exit. This can only be achieved by transmitting the beam through a zero-power optical device as that of a plane parallel plate. In this section, we discuss the design and function of such a device that we will call 'Zerogon.' The Zerogon has an outer curved surface and would not deviate nor shift the beam laterally on transition. In the current application, the outer curved surface of the Zerogon 1 carries the curved mask 2.

The Zerogon 1 has two identical menisci with their radii of curvature set by Eqn. (9) and the elements grouped in close proximity, with their concave surfaces facing each other as shown in Figure 8. The outer surface holds the flexible mask 2 close enough using a locking band 9. The goal of designing such an optics device is to make the small-sized illuminating beam transmit through the optic at any height from the optical axis of the Zerogon without any deviation or shift to preserve the concept of providing constant partial coherence factor for the sake of obtaining better resolution and contrast in curved mask lithography. As proved in this section, the symmetry of the configuration cancels out the lateral shifts introduced by each meniscus without deviating the ray through the system and thus preserving the numerical aperture of the condenser and resolution characteristics of the projection system. Notice that the lookalike Hypergon on the other hand, is an imaging system as shown in Figure 7, with construction and performance significantly different from that of the Zerogon. Figure 7 shows how the Hypergon of PRIOR ART has lens power. Figure 9 shows how the placement of the mask 2 on the convex exit surface of the Zerogon 1, with the focus on the curved mask 2, allows for proper focus of the projected beam onto the curved substrate 3.

We may now extend the above raytracing equations to Zerogon. In order to work out a Zerogon, let us consider a lens doublet of two identical menisci with concave surfaces facing each other. Let us assume that the second meniscus element, separated from the first meniscus by a distance t_2, has radii of curvature R_3 and R_4 and thickness t_3. The transfer equation to third surface may now be written as

$$y_3 = y_2 + t_2 u_2' \tag{11}$$

and refraction at third surface yields

$$u_3' = \frac{n u_3}{n'} - \frac{y_3 (n' - n)}{R_3 n'} \tag{12}$$

In view of identical menisci for Zerogon, we can write

$n=1, n'=N$ and $u_3=u_2'$ for third surface;

$n=N$, $n'=1$ and $u_4=u_3'$ for fourth surface;

$R_3= -R_2$ and $R_4= -R_1$ and $t_3=t_1$.

Substitution of Eqn.(11) in the above equation gives us

$$u_3' = \left[\frac{1}{N} + \left(\frac{N-1}{N}\right)\frac{t_2}{R_2}\right] u_2' + \left(\frac{N-1}{N}\right)\frac{y_2}{R_2} \tag{13}$$

Transfer to fourth surface may now be written as

$$y_4 = y_3 + t_3 u_3'$$

Substitution of Eqns.(11) - (13) and further simplification leads to

$$y_4 = \left[1 + \left(\frac{N-1}{N}\right)\frac{t_1}{R_2}\right] y_2 + \left[t_2 + t_1\left(\frac{1}{N} + \left(\frac{N-1}{N}\right)\frac{t_2}{R_2}\right)\right] u_2' \tag{14}$$

For an axial ray or ray incident at a height y_1 from optical axis with $u_1=0$ and thus $u_2'=0$, Eqns. (6), (7) and (9) yield

$$y_4 = \left(1 + \frac{\Delta R}{R_2}\right) y_2 = y_1$$

Thus a Zerogon would not cause any shift in the height of the axial ray unlike a single meniscus lens. Now, let us see the deviation of a ray produced by the device.

The equation for refraction at fourth surface may now be written as

$$u_4' = \frac{nu_4}{n'} - \frac{y_4(n'-n)}{R_4 n'}$$
$$= Nu_3' - \frac{(N-1)}{R_1} y_4$$

Use of Eqns. (13) and (14) in the above equation and further simplification yields

$$u_4' = \left[1 + \frac{(N-1)t_2}{R_1R_2}\left[\Delta R - \frac{(N-1)}{N}t_1\right] - \frac{(N-1)}{N}\frac{t_1}{R_1}\right]u_2' + \frac{(N-1)}{R_1R_2}\left[\Delta R - \frac{(N-1)}{N}t_1\right]y_2$$

Using Eqn.(6) for u_2' and Eqn.(5) for y_2 there in, we get

$$u_4' = \left[1 + \frac{(N-1)t_2}{R_1R_2}\left(\Delta R - \frac{(N-1)}{N}t_1\right) - \frac{(N-1)}{N}\frac{t_1}{R_1}\right] \times \left[\left(1 + \frac{(N-1)}{N}\frac{t_1}{R_2}\right)u_1 - (N-1)\left(\Delta R - \frac{(N-1)}{N}t_1\right)\frac{y_1}{R_1R_2}\right] + \frac{(N-1)}{R_1R_2}\left(\Delta R - \frac{(N-1)}{N}t_1\right)y_2 \quad (15)$$

It is now easy to explain how Eqn.(9) could help a Zerogon achieve the function of the required illumination compensator without deviation and shift of a ray. When Eqn.(9) is satisfied, Eqn.(15) can be simplified to

$$\begin{aligned} u_4' &= \left(1 - \frac{(N-1)}{N}\frac{t_1}{R_1}\right)\left(1 + \frac{(N-1)}{N}\frac{t_1}{R_2}\right)u_1 \\ &= \left(1 - \frac{\Delta R}{R_1}\right)\left(1 + \frac{\Delta R}{R_2}\right)u_1 \quad (16) \\ &= u_1 \end{aligned}$$

A numerical example

The Zerogon worksheet below illustrates the calculations for a sample Zerogon worked out for an outer radius of curvature of R = 50 mm and thickness

of 10 mm. The calculations were done for a displaced axial ray and an off-axial ray entering the lens with an angle. Initially it is required to compute the inner radius of curvature of the meniscus elements for a given value of radius on the outer surface using Eqn. (9) and then the above set of equations or any standard optical design software can be used to evaluate the design. The paraxial raytrace values of a given ray as given in the table may be compared with the real raytrace values that fall in close agreement with each other.

Parameter/ i	0	1	2	3	4
t_i		10.000	12.000	10.000	
n_i'		1.509	1.000	1.509	1.000
R_i		-50.000	-46.627	46.627	50.000
y_i		12.500	11.657	11.657	12.500
u_i	0.000	0.000	-0.084	-0.084	0.000
y_{pi}		10.632	8.011	1.848	-0.061
u'_{pi}	-0.276	-0.254	-0.294	-0.187	-0.276

It may be seen that the Zerogon preserves y_i , u_i , and u'_{pi} of any given ray on first and fourth surfaces, having the same functional properties as that of a plane parallel plate. In fact, it is easier to prove and visualize the Zerogon as equivalent to a pair of plane parallel plates separated by the same distance as that of menisci in Zerogon. The optical path length variation for any arbitrary ray in meniscus elements is compensated by the altered air path between the menisci.

An application of the Zerogon is its use at intermediate curved image surfaces with the image surface falling on Zerogon's outer surface whose radius of curvature could be designed to the field curvature of the optics in front of the Zerogon. The description and example above emphasize its behavior equivalent to that of a plane parallel plate with curved surfaces. Hence, wherever a plane parallel plate has to be replaced by an optic with curved surfaces, the Zerogon could be used without affecting the performance of the whole system.

Use of Zerogon for curved lithography.

As described earlier, the illuminated beam from the condenser could be effectively coupled to the projection lens by resting the curved mask on an optical device that transmits the beam undistorted. A Zerogon with its outer radius of curvature to match with that of the substrate and a membrane mask will be precisely stretched and secured over the outer surface by a frame to fix its position. The Zerogon-curved mask combination works just like that of a planar mask providing an efficient coupling between illumination system and the imaging system for curved lithography. Figure 9 is a schematic of the functionality of the Zerogon / mask combination and how the necessary diffraction orders are collected by the projection lens.

Conclusi n

Special Merits of the Curved Mask Compensator

The illumination system is a very important part of the lithographic tool. It plays an important role in controlling the performance of the lithographic system. The field of projection lithography using planar masks and substrates has witnessed several important innovations in the field of illumination engineering that significantly improved the resolution and contrast of projection patterning. Projection lithography on curved substrates needs efficient illumination techniques to illuminate curved masks. The illuminating beam displaced and deviated by the bulk of a thick curved mask when used alone, needs to have a compensator in front of the mask for best results.

We discussed a novel optics device, called Zerogon, that has curved optical elements exhibiting zero total power and performs as good as a plane parallel plate causing no deviations to the incoming radiation. Having this unique null property Zerogon is expected to serve various applications as an alternative to plane parallel plate. We also use the Zerogon with curved mask on one of its outer surfaces, making the whole device very efficient in coupling the illumination beam to the imaging system.

Another important merit of this invention is that the two meniscus elements can also be arranged back-to-back on convex surfaces with concave outer surfaces and make the device still carry the same properties described above for Zerogon. Hence either configuration could be referred to as part of the present invention.